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On the Statistics of El Niño Occurrences and the Relationship of El Niño to Volcanic and Solar/Geomagnetic Activity

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ABSTRACT

El Niño is conventionally defined as an anomalous and persistent warming of the waters off the coasts of Ecuador and Peru in the eastern equatorial Pacific, having onset usually in southern hemispheric summer/fall. Examined here are some of the statistical aspects of El Niño occurrences, especially as they relate to the normal distribution and to possible associations with volcanic, solar, and geomagnetic activity. For example, the elapsed time between successive onsets of near moderate-to-stronger El Niño (over the last century and a half) is about 3.7 ± 0.6 years (at the 95 percent level of confidence), having a standard deviation of 1.8 +0.6/−0.3 years, a range of 1 to 8 years, and a median/mode value of 3 years. The distribution of elapsed times between successive onsets appears normally distributed, although a positive skew is clearly seen and greater variation has occurred within the last 50 to 75 years. For the interval 1848 to 1987, El Niño events of moderate strength outnumber those of strong intensity by 24 to 14, and, as yet, there has never been a single occurrence of back-to-back strong events.

A comparison of El Niño onsets to major volcanic activity (where a major eruption is taken to be one whose Volcanic Explosivity Index VEI ≥4 and/or Dust Veil Index DVI ≥250) results in the following: About 40 and 60 percent, respectively, of the El Niño events are preceded within one or two years by major volcanic eruptions in the tropics, while about 70 and 80 percent, respectively, are preceded within one or two years by major eruptions somewhere in the world (i.e., ignoring latitude). Also, a number of El Niño events cannot be directly linked with any known major volcanic eruption that preceded them within three years (some within several), the most recent example being the 1972-73 strong El Niño.

A comparison of El Niño onsets to specific phases of the solar/geomagnetic cycles results in the following: Nearly two-thirds of the El Niño events had their onsets when annual sunspot number was below 54.3 (the average annual sunspot number for the interval 1848 to 1987), the bulk (about 70 percent) of which were moderate in strength. For Cycles 10 to 22, every sunspot cycle either had an onset of El Niño during the window ± 1 year from solar minimum or already had one in progress at that time (Cycle 13). Also, about 70 percent of the El Niño events had their onsets during the declining portion of the sunspot cycle (which corresponds to the interval when geomagnetic activity is usually greatest), with 12 out of 14 (about 85 percent) strong El Niño events having onsets during the declining portion of the sunspot cycle. Lastly, evidence was found (at ≥95 percent level of confidence) favoring an inverse correlation between the number of El Niño events per sunspot cycle and the size of the cycle, which, if true, suggests that fewer than three El Niño events may occur during the present sunspot cycle (Cycle 22: 1986 to ca. 1996) and that more El Niño events may have occurred, on average, during the Maunder minimum (1645 to 1715).

With regard to the "very strong" El Niño of 1982–83, it is noted that, although it may very well be related to the 1982 eruptions of El Chichón, the event occurred essentially "on time" (with respect to the past behavior of elapsed times between successive El Niño events; a moderate-to-stronger El Niño was expected during the interval 1978 to 1982, assuming that El Niño occurrences are normally distributed, having a mean elapsed time between successive onsets of 4 years and a standard deviation of 2 years and a last known occurrence in 1976). Also, although not widely recognized, the whole of 1982 was a record year for geomagnetic activity (based on the aa geomagnetic index, with the aa index registering an all-time high in February 1982), perhaps, important for determining a possible "trigger" for this and other El Niño events.

A major feature of this study is an extensive bibliography (325 entries) on El Niño and volcanic-solar-geomagnetic effects on climate. Also, included is a tabular listing of the 94 major volcanic eruptions of 1835 to 1986.

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NASA TECHNICAL PAPER

ON THE STATISTICS OF EL NIÑO OCCURRENCES AND THE RELATIONSHIP OF EL NIÑO TO VOLCANIC AND SOLAR/GEOMAGNETIC ACTIVITY

I. INTRODUCTION

The term "El Niño" was originally used to describe the annual warming of the waters off the western coast of South America (in particular, Ecuador and Peru) near to just following Christmas. As such, El Niño was regarded as a purely regional and short-lived oceanic phenomenon, of little interest to people living outside the immediate area and of little consequence in relation to the world's weather and climate.

Within the past 25 years, however, this perception has radically changed. For example, today the term "El Niño" is applied exclusively to only those anomalous and pervasive warmings of the coastal waters off Ecuador and Peru that are of a more persistent and intense nature, lasting typically several months to more than a year and occurring once every few to several years [52, 221]. Further, changes in sea surface temperature (SST) in the eastern/central equatorial Pacific, which is the primary oceanographic signal for El Niño and its counterpart, "La Niña" (also called "Warm Event" and "Cold Event," respectively), have been found to often correlate with changes in the difference of atmospheric sea level pressure (SLP) between widely separated stations in the Pacific Basin (typically, Tahiti or Easter Island and Darwin, Australia; this difference is called the "Southern Oscillation Index" or SOI and serves as the primary atmospheric signal for the Southern Oscillation, a somewhat orderly rearrangement or progression of meteorological phenomena in the region of the Indian and Pacific Oceans); hence, El Niño is now perceived to be part of a large-scale, dynamic, atmospheric-oceanic, climatic feedback system of global proportion [1, 7-8, 12-15, 18, 20, 34-36, 39-41, 63-64, 69, 74, 86, 89, 91, 101, 106, 116-117, 128, 135-136, 138, 148, 162, 173, 178, 181, 189, 192, 195, 201, 206-210, 220, 225-229, 231-234, 238, 244-246, 249, 273-274, 286-287, 309-311, 313-316, 318-320].

While it is generally accepted that El Niño and the Southern Oscillation are different manifestations of a single, large-scale, dynamic, air-sea, climatic feedback system (often called "ENSO"), the inferred coupling has been somewhat less than perfect. For example, Deser and Wallace [52], based on the 1925 to 1986 interval, have found several instances when El Niño preceded the onsets of positive SLP at Darwin, Australia, and a few instances when El Niño followed the onsets of positive SLP (including the largest El Niño of the century: the 1982-83 event). More peculiarly, they also found instances when El Niño and negative swings in the SOI occurred separately. Thus, they concluded that El Niño and the Southern Oscillation are "more loosely coupled" than previous studies would imply and that "there are strong local controls on the climate of the eastern equatorial Pacific that sometimes transcend the influence of the Southern Oscillation."

Models for predicting/hindcasting ENSO are deterministic in nature; i.e., a change in an important oceanographic/atmospheric parameter (e.g., SST, SLP, SOI, outgoing longwave radiation, surface wind stress, sea surface salinity, sea level height, the depth of the thermocline, etc.) is either randomly or stochastically forced to bring about conditions favoring the development of an El Niño.

While sometimes the forcing is introduced from the extratropics (via any one of a number of teleconnection processes), the forcing more often is introduced from entirely within the tropical Pacific region alone, where coupled interactions between the atmosphere and ocean are strongest [11, 16, 27-29, 35-38, 66, 70-71, 80, 87-88, 98-99, 124-125, 153, 156-158, 174, 180, 183, 207, 216, 248, 260, 275, 288-289, 292, 317, 321-323].

Because of the near simultaneity of two of the largest climatic events of the century, the early 1982 eruptions of El Chichón in the northern tropical region of Mexico and the abrupt late-1982 appearance of El Niño (which followed El Chichón by about two seasons), much speculation has been raised that an association exists between them. In particular, because major volcanic eruptions are known to change the optical properties of the Earth's atmosphere (especially the stratosphere), it has been suggested that alteration of the atmospheric circulation occurs, leading either to conditions favorable for the initiation of El Niño (thus acting as the "trigger") or to an intensification of an El Niño that is already in progress (thus modulating the severity of the El Niño) [94-96, 110, 196, 202, 229, 252, 257].

Some of the statistical aspects of El Niño occurrences are examined here. In particular, the statistical properties of the distribution of elapsed time between successive onsets of El Niño and the possible associational aspects of El Niño occurrences, with respect to both volcanic and solar/geomagnetic activity, are examined. Reexamination of the association between volcanic activity and El Niño is prudent because recent reports have presented conflicting results [94-95, 196, 202]. Similarly, examination of the association between solar/geomagnetic activity and El Niño, as yet to be explored, may yield results that are pertinent to El Niño prediction (in a "general" sense, not necessarily a "causal" sense). Finally, some remarks are given which may be of use for predicting the occurrence of the "next" anticipated El Niño.

II. DATA

Listings of El Niño events can be found in Quinn et al. [221-222], Rasmusson [231], van Loon and Shea [278], Deser and Wallace [52], and Ropelewski and Jones [247], with the Quinn et al. [221] listing being the most complete. The Quinn et al. [221] listing catalogs 79 El Niño events of near moderate-to-very strong intensity that appear to have occurred off "the west coast region of northern South America and its adjacent Pacific Ocean waters" during the interval 1525 to 1987, with events of moderate intensity (32) extending back to 1806. (No weak events are cataloged.) The Quinn et al. [221] listing represents a revision of an earlier listing (Quinn et al. [222]) and describes the very-strong, strong, and moderate events in the following manner: "The very strong events show extreme amounts of rainfall, flood waters, and destruction, and coastal SST's usually reach values 7° to 12 °C above normal during some months of the southern hemisphere summer and fall seasons. The strong events, in addition to showing large amounts of rainfall and coastal flooding and significant reports of destruction, exhibit coastal SST's in the 3° to 5 °C above normal range during several months of the southern hemisphere summer and fall seasons. The moderate events in addition to showing above normal rainfall, some flooding, and small amounts of destruction, generally show coastal SST's in the 2° to 3 °C above normal range for several months during the southern hemisphere summer and fall seasons. In all three categories the effects on coastal fisheries are highly damaging."

Extensive listings of volcanic eruptions can be found in Lamb [154], Simkin et al. [262], Newhall and Self [194], Handler [94-96], and Bradley [19]. Major volcanic eruptions are usually described as those having a Dust Veil Index (DVI) ≥250 or a Volcanic Explositivity Index (VEI) ≥4. As an example, Lamb [154] notes that the great eruption of 1815 (Tambora), the "largest and deadliest volcanic eruption in recorded history" (Stothers [267]), and had a DVI of about 3,000, while the great eruption of 1883 (Krakatau) had a DVI of about 1,000; according to Newhall and Self [194], the VEI associated with these explosions measured 7 and 6, respectively, implying column heights ≥25 km, ejecta volumes $\geq 10^{10}$ m^3, and significant perturbation of the stratosphere. The stratospheric aerosols associated with major volcanic eruptions, because of deposition on ice sheets in Greenland and Antarctica, likewise, have been used to indicate the presence of major volcanic eruptions [51, 92-93, 160, 168], as have estimates of atmospheric optical depth (Pollack et al. [215]). In the listings of Lamb [154] and Newhall and Self [194], the interval examined was from 1500. Also, it should be noted that the volcanic record may be incomplete for VEI ≤4 for the period prior to about 1950 or 1960 [194, 228].

Sunspot (Zürich/International sunspot number) and geomagnetic (the aa index) data are reliably known back to about 1848 and 1868, respectively [61, 166-167, 176, 205, 299], while other solar/geomagnetic parameters are of a more recent vintage. For example, the Ap index is known back to 1932, 10.7-cm solar radio flux back to 1947, and satellite measurements of the solar constant only back to 1978 (Nimbus 7, N-7) or 1980 (Solar Maximum Mission, SMM).

III. RESULTS

Table 1 lists 39 El Niño events, from the aforementioned Quinn et al. [221] listing, that occurred between 1840 to 1987 and that were of nearly moderate-to-very strong intensity (strength). Also identified in Table 1 are the particular years associated with each El Niño event and notes referring to results from other studies (e.g., Rasmusson [231]; van Loon and Shea [278]; Ropelewski and Jones [247]). These 39 events include 15 "strong" (S, S+, VS) and 24 "moderate" (W/M, M, M+) events. A general note and a table legend appear at the bottom of Table 1. It is interesting to note that of the 28 Warm Events cataloged by van Loon and Shea [278], 24 are also found in Table 1. The only events appearing in van Loon and Shea that do not appear in Table 1 are for the years 1904, 1913, 1963, and 1969; of these, the years 1963 and 1969 were El Niño years, but the El Niño events were of weaker strength. Likewise, excluding event 39 which does not appear in Rasmusson [231], of the remaining 38 events, all appear in Rasmusson's listing, except events 5 (1860), 10 (1874), and 20 (1907); i.e., 35 out of 38 of the regionally determined El Niño events were also on a list of El Niño events that were clearly of global proportions. Thus, while Quinn et al. [221] identified their El Niño events, from which Table 1 is merely an extraction, primarily from local/regional effects, the events are truly global in extent.

Table 2 lists 94 known volcanic eruptions that occurred between 1835 and 1986 that either had DVI ≥50, VEI ≥4, or an observed dust cloud of column height ≥15 km and that may have had significant stratospheric effects. A column height of ≥15 km was selected as a criterion because in the tropics the tropopause (the dividing region between the upper troposphere and the lower stratosphere) averages above 15 km, while at mid and high latitudes, the height of the tropopause is below 15 km. The list of volcanic eruptions was adapted primarily from lists tabulated by Lamb [154], Newhall and Self [194], and Handler [94], with additions also from *Eos* (appearing in the column entitled "Geophysical Events") and from Toon and Pollack [272] (cf. Baldwin et al. [9]; Pollack et al. [215]) for the period 1968 to 1986.

TABLE 1. SUMMARY OF EL NIÑO EVENTS: 1840-1987
(From Quinn et al. [221])

Event No. (i)	Year	Strength	Notes
1	1844-45	S+	R: 1844–46; 2, 4, 3
2	1850	M	R: 1850; 2
3	1854	W/M	R: 1854; nc
4	1857-58	M+	R: 1857; 2
5	1860	M	Not Listed
6	1864	S	R: 1864; 4; WE
7	1866	M	R: 1866; nc
8	1867-68	M	R: 1868; 3; WE (1868)
9	1871	S+	R: 1871; 3
10	1874	M	Not Listed
11	1877-78	VS	R: 1877-78: 4, 4; WE (1877)
12	1880	M	R:1880; 3; WE
13	1884	S+	R: 1884-85; 4,3; WE
14	1887-89	W/M	R: 1887-89; 3, 3, 1; WE (1888); Low (1888)
15	1891	VS	R: 1891; 4; WE
16	1896-97	M+	R: 1896; 3; WE (1896); Low (1896)
17	1899-1900	S	R: 1899-1900; 4, 3; WE (1899); Low (1900)
18	1902	M+	R: 1902; 3; WE; Low (1902)
19	1905	W/M	R: 1905; 3; Low (1905)
20	1907	M	Not Listed
21	1911-12	S	R: 1911-12; 4, 3; WE (1911); Low (1911)
22	1914	M+	R: 1914; 3
23	1917	S	R: 1917; 2
24	1918-19	W/M	R: 1918-19; 4, 3; WE (1918); Low (1918-19)
25	1923	M	R: 1923; 2; WE; Low (1923)
26	1925-26	VS	R: 1925-26; 4, 4; WE (1925); Low (1925-26)
27	1930-31	W/M	R: 1929-30; 3, 3; WE (1930)
28	1932	S	R: 1932; 2; WE
29	1939	M+	R: 1939; 3; WE; Low (1939)

TABLE 1. (Concluded)

Event No. (i)	Year	Strength	Notes
30	1940-41	S	R: 1940-41; 2, 4; Low (1939-41)
31	1943	M+	R: 1943-44; 2, 2
32	1951	W/M	R: 1951; 2; WE; Low (1951)
33	1953	M+	R: 1953; 3; WE; Low (1953)
34	1957-58	S	R: 1957-58; 4, 4; WE (1957); Low (1957)
35	1965	M+	R: 1965; 3; WE; Low (1965)
36	1972-73	S	R: 1972-73; 4, 4; WE (1972); Low (1972)
37	1976	M	R: 1975-76; 1, 3; WE
38	1982-83	VS	R: 1982-83; 4, 4; WE (1982); Low (1982-83)
39	1987	M	Not Listed

Legend: W/M – Nearly moderate
M – Moderate
M+ – Nearly strong
S – Strong
S+ – Nearly very strong
VS – Very strong
R – Rasmusson [231]
1 – Very weak
2 – Weak
3 – Moderate
4 – Strong
nc – Not classified
WE – Warm event (episode)

NOTE: The Rasmusson [231] listing, adapted from Quinn et al. [222], also identifies El Niño events in 1852 (2), 1855 (2), 1862 (nc), 1873 (2), 1875 (1), 1946 (1), 1948 (1), 1963 (1), and 1969 (2). Of these, the events of 1963 and 1969 have been classified by van Loon and Shea [278] as warm events; the years 1904 and 1913 were also classified as warm events, although no counterpart El Niño event appears in either the Quinn et al. [221] or Rasmusson [231] lists for these two years. An event marked "Low" means that during the given year the Tahiti-Darwin Southern Oscillation Index remained in the lower 25 percent of the distribution for five months or longer (Ropelewski and Jones [247]); other "Low" years include 1913, 1946, 1963, 1969, and 1977. The term "Not Listed" means that the event does not appear in Rasmusson [231]. One should also note that on occasion there is a difference in the strength (intensity) classification in the various lists of El Niño.

TABLE 2. SUMMARY OF VOLCANIC ERUPTIONS WITH POSSIBLY SIGNIFICANT STRATOSPHERIC EFFECTS: 1835-1986

(Adapted from Lamb [154], Newhall and Self [194], Handler [94], and descriptions reported in *Eos* (i.e., dust clouds at ≥15 km; Note: L – Lamb, NS – Newhall and Self, H – Handler, and E – *Eos*). Events noted as NS after 1869 also appear in Handler [94-95], and those events with possible well-defined signatures in either Greenlandic and/or Antarctic ice core deposits are denoted with an asterisk, taken from Hammer [92], Hammer et al. [93], and Legrand and Delmas [160].)

Year	Volcano	Location (Degrees)	Notes
1835	Coseguina	13 N, 88 W	NS; VEI = 5 (L; DVI = 4000); *
1845	Hekla	64 N, 20 W	NS; VEI = 4 (L; DVI = 800); *
1846	Amargura	18 S, 174 W	L; DVI = 1000; *
1849	Purace	2 N, 76 W	NS; VEI = 4
1852	Etna	38 N, 15 E	L; DVI = 100 (50)
1852	Mauna Loa	20 N, 156 W	L; DVI = 250
1852	Gunung Api	4 S, 130 E	L; DVI = 200
1853	Chikurachki	50 N, 155 E	NS; VEI = 4
1854	Sheveluch	57 N, 162 E	NS; VEI = 5 (L; DVI = ?)
1855-56	Cotopaxi	1 S, 78 W	L; DVI = 700; *
1856	Awu	4 N, 126 E	L; DVI = 70
1856	Sangihe	4 N, 126 E	L; DVI = 500?
1856	Komagatake	42 N, 141 E	NS; VEI = 4 (L; DVI <10)
1861	Makjan	1 N, 128 E	L; DVI= 800; *
1869	Purace	2 N, 76 W	NS; VEI = 4
1869	Cebcruco	21 N, 105 W	L; DVI = 70 (50)
1872	Vesuvius	41 N, 14 E	L; DVI = 150 (70)
1872	Merapi	8 S, 110 E	L; DVI = 80
1872	Sinarka	50 N, 155 E	NS; VEI = 4
1873	Grimsvotn	64 N, 17 W	NS; VEI = 4 (L; DVI = 30)
1875	Askja	65 N, 17 W	NS; VEI = 5 (L; DVI = 1000); *
1876	Suwanose-Zima	30 N, 17 W	NS; VEI = 4
1877	Cotopaxi	1 S, 78 W	NS; VEI = 4 (L; DVI = 50)
1881	Nasu	37 N, 140 E	NS; VEI = 4
1883	Krakatau	6 S, 105 E	NS; VEI = 6 (L; DVI = 1000); *
1883	Augustine	59 N, 153 W	NS; VEI = 4 (L; DVI = 70)
1885	Falcon Island	20 S, 175 W	L; DVI = 300
1886	Tarawera	38 S, 177 E	NS; VEI = 5 (L; DVI = 800);*
1886	Tungurahua	1 S, 78 W	NS; VEI = 4
1886	Niafu	16 S, 176 W	L; DVI = 300; *
1888	Bandai san	38 N, 140 E	NS; VEI = 4 (L; DVI = 500);*
1888	Ritter Island	6 S, 148 E	L; DVI = 250

TABLE 2. (Continued)

Year	Volcano	Location (Degrees)	Notes
1889	Suwanose-Zima	30 N, 130 E	NS; VEI = 4
1890	Bogoslof	54 N, 168 W	L; DVI = 170 (50)
1892	Awu	4 N, 126 E	L; DVI = 100
1895/96	Thompson Island	54 S, 5 E	L; DVI = 1300 (400); *; Island destroyed
1898	Una Una	0 S, 121 E	L; DVI = 140
1899	Doña Juana	2 N, 77 W	NS; VEI = 4
1902	Mont Pelée	15 N, 61 W	NS; VEI = 4 (L; DVI = 100); Two eruptions of VEI = 4
1902	Soufrière (St. Vincent)	13 N, 61 W	NS; VEI = 4 (L; DVI = 300); *
1902	Santa Maria	15 N, 92 W	NS; VEI = 6 (L; DVI = 600); *
1903	Thordarhyrna	64 N, 18 W	NS; VEI = 4
1906-07	Bogoslof	54 N, 168 W	L; DVI = 70 (20)
1907	Shtyubelya Sopka (Ksudach)	52 N, 158 E	NS; VEI = 5 (L; DVI = 500); *
1909	Tarumai	43 N, 141 E	NS; VEI = 4
1911	Taal	14 N, 121 E	NS; VEI = 4 (L; DVI = 30)
1912	Katmai (Novarupta)	58 N, 155 W	NS; VEI = 6 (L; DVI = 500); *
1913	Colima	19 N, 104 W	NS; VEI = 4? (L; DVI = 10)
1914	Sakurashima (Sakurazima)	32 N, 131 E	NS; VEI = 4 (L; DVI = 40)
1917	Agrigan	19 N, 146 E	NS; VEI = 4
1918	Tungurahua	1 S, 78 W	NS; VEI = 4
1918	Katla	64 N, 19 W	NS; VEI = 4
1919	Manam	4 S, 145 E	NS; VEI = 4
1921	Andes (Puyehue)	41 S, 72 W	NS; VEI = 4 (L; DVI = 200)
1924	Raikoke	48 N, 153 E	NS; VEI = 4
1929	Komaga-Take	42 N, 141 E	NS; VEI = 4
1931	Kluchev (Kliuchevskoi)	56 N, 161 E	NS; VEI = 4 (L; DVI = 5)
1932	Fuego	14 N, 91 W	NS; VEI = 4
1932	Quizopu (Cerro Azul)	36 S, 71 W	NS; VEI = 5 (H; 6) (L; DVI = 70)
1937	Rabual	5 S, 152 E	NS; VEI = 4?
1945	Kliuchevskoi	56 N, 161 E	NS; VEI = 4
1946	Sarychev	48 N, 153 E	NS; VEI = 4
1947	Hekla	64 N, 20 W	NS; VEI = 4 (L; DVI = 70); * Dust cloud to 27 km
1951	Mt. Lamington	9 S, 148 E	NS; VEI = 4 (L; DVI = 20)
1951	Ambryn	16 S, 158 E	NS; VEI = 4
1952	Bagana	6 S, 155 E	NS; VEI = 4
1953	Mt. Spurr	61 N, 153 W	NS; VEI = 4 (L; DVI = 7); Dust cloud to 23 km
1955	Nilahue	40 S, 72 E	NS; VEI = 4
1956	Bezymjannaja (Bezymianny)	56 N, 161 E	NS; VEI = 5 (L; DVI = 30) Dust cloud to 45 km

TABLE 2. (Concluded)

Year	Volcano	Location (Degrees)	Notes
1960	Puntiagudo	42 S, 72 W	L; DVI = 100 (50) Several other vents (unnamed); Given latitude/longutude is average
1963	Gunung Agung (Agung)	8 S, 116 E	NS; VEI = 4 (L; DVI = 800); *
1964	Sheveluch	57 N, 162 E	NS; VEI = 4
1965	Taal	14 N, 121 E	NS; VEI = 4 (L; DVI = 10-15)
1966	Kelut	8 S, 112 E	NS; VEI = 4
1966	Awu	4 N, 126 E	NS; VEI = 4 (L; DVI = 50-100) Dust cloud to 18 km
1966	Oldoinyo Lengai	3 S, 36 E	NS; VEI = 4
1968	Fernandina	0 S, 92 W	NS; VEI = 4 (L; DVI = 50-100)
1973	Tiatia	44 N, 146 E	NS; VEI = 4
1974	Fuego	14 N, 91 W	NS; VEI = 4
1975	Plosky Tolbachik	56 N, 160 E	NS; VEI = 4
1976	Augustine	59 N, 153 W	NS; VEI = 4
1977	Bezymianny	56 N, 161 E	E; Dust cloud to 15 km
1979	Bezymianny	56 N, 161 E	NS; VEI = 4
1979	Soufrière	13 N, 61 W	E; Dust cloud to 18 km
1980	Mt. St. Helens	46 N, 122 W	NS; VEI = 5; E; Dust cloud to ≥19 km
1980	Hekla	64 N, 20 W	E; Dust cloud to 15 km
1980	Gareloi	52 N, 179 W	E; Dust cloud to 10.5 km; SO_4 at 19.2 km
1981	Alaid	51 N, 156 E	E; Dust cloud to 15 km
1982	Mystery		E; Dust at 10-20 km (January-March); Several eruptions possibly associated with cloud
1982	El Chichón	17 N, 93 W	H; VEI = 4; E; Dust cloud to 16.8 km (possibly to 26 km)
1983	Mystery		E; Dust at 18-19 km (February-April)
1984	Home Reef	19 S, 175 W	E; Dust cloud to 15 km
1985	Nevado del Ruiz	5 N, 75 W	E; Dust cloud to 10.5 km (possibly to 25 km)
1986	Pavlof	55 N, 162 W	E; Dust cloud to 16 km

NOTE: Another list of volcanic eruptions that may have produced significant amounts of stratospheric aerosols appears in Handler [96]. This list differs from his previous lists (Handler [94-95]) in that three eruptions were removed as possible contributors of stratospheric aerosols (1973 – Tiatia; 1975 – Plosky Tolbachik; and 1979 – Bezymianny), while 10 were added (August 1928 – Paluweh, 8 S, 121 W; 1929 – Reventador, 0 S, 77 W; September 1971 – Fuego, 14 N, 91 W; April 1979 – Soufrière, 13 N, 61 W; November 1979 – Sierra Negra, 1 S, 91 W; October 1980 – Ulawun, 5 N, 151 E; April 1981 – Alaid, 51 N, 156 E; May 1981 – Pagan, 18 N, 146 E; December 1981 – Nyamuragira, 1 S, 29 E; and July 1983 – Una Una, 0 S, 122 E). Many of these latter additions, however, must be considered as marginal contributors in that only slight enhancements in the integrated non-Rayleigh backscatter coefficient (Mauna Loa, Hawaii) during the period December 1974 – June 1987 were observed (Geophysical Events [79]). The December 1981 eruption of Nyamuragira may have been the source of the Mystery event of early 1982.

The year of the eruption, its name and location, and notes regarding each of the entries are given. An asterisk (*) denotes those events which also have a reported signature in the ice core deposits of either Greenland or Antarctica. Of the 94 events, 92 can be associated with specific volcanic eruptions of known location; two are denoted "Mystery." (The mystery cloud of 1982 may be associated with Nyamuragia, located at 1 S, 29 E, that erupted in December 1981; Handler [96].) Excluding the two mystery aerosols, 45 occurred within the tropics (within 23.5 degrees of the equator, a region containing about 40 percent of the Earth's surface area, predominantly water, as well as the bulk of the Earth's atmosphere). In particular, 23 occurred in the northern tropics, 22 occurred in the southern tropics, 41 occurred north of 23.5 N (the bulk of which occurred north of 45 N), and 6 occurred south of 23.5 S (the bulk of which occurred between 23.5 S and 45 S). Also, of the 94 eruptions, 17 have been clearly identified in ice core deposits (perhaps, 18; evidence has been presented by Hofmann et al. [114] that the El Chichón stratospheric aerosol was detected in Antarctica).

Plotted in Figure 1 are the annual averages of sunspot number, 10.7-cm solar radio flux, the aa and Ap geomagnetic indices, and solar irradiances (SMM and N-7) for data available periods during the interval 1840 to 1987. The long-term average for each of these parameters is drawn as the horizontal line. As an exammple, 54.3 represents the average annual sunspot number for the interval 1848 to 1987, 129.5 represents the average annual 10.7-cm solar radio flux value for the interval 1947 to 1987, and so on. Individual sunspot cycles are identified at the bottom of Figure 1. Across the top of Figure 1 are the 39 El Niño events given in Table 1 and the 94 possibly significant volcanic eruptions given in Table 2, where the shaded triangles denote "strong" El Niño events and tropical volcanic eruptions, respectively. The term "VS" means that the El Niño was very strong. (The mystery aerosol of 1982 has been shaded based on the remarks previously given; Handler [96].)

In the next section, discussion will center on Figure 1 (and the supporting Tables 1 and 2). It is upon this set of comparative results that the bulk of the remaining text is concerned.

IV. DISCUSSION

A. Statistical Aspects of El Niño Onsets

From Figure 1 and Table 1, one notes that 38 El Niño events of nearly moderate to very strong intensity occurred during the 140-year history of modern era sunspot observations (1848 to present). Of these 38 events, 24 have been of moderate (W/M, M, M+) intensity and 14 of strong (S, S+, VS) intensity. Thus, on average, El Niño occurs at the rate of one event per 3.7 years or, incorporating intensity, at the rates of one moderate event per 5.8 years and one strong event per 10 years. It may also be noteworthy that every decade between the 1840's and the 1980's, except the 1960's, had a moderate to stronger El Niño that spanned two consecutive years (e.g., 1911-12, 1925-26, etc.; see Table 1) and that there has never been a single instance of back-to-back strong El Niño events.

In Figure 2 (top-left), the elapsed time (in years) between successive onsets of El Niño is plotted as a function of event number (see Table 1). As noted above, the mean interval between onsets of El Niño is about 3.7 years, identified in Figure 2 as the horizontal line running parallel to the event number axis. The sample of 38 elapsed times has a standard deviation of about 1.8 years and a mode and median of 3 years. A runs test (Lapin [155], p. 624) suggests that the sample of elapsed times is randomly distributed,

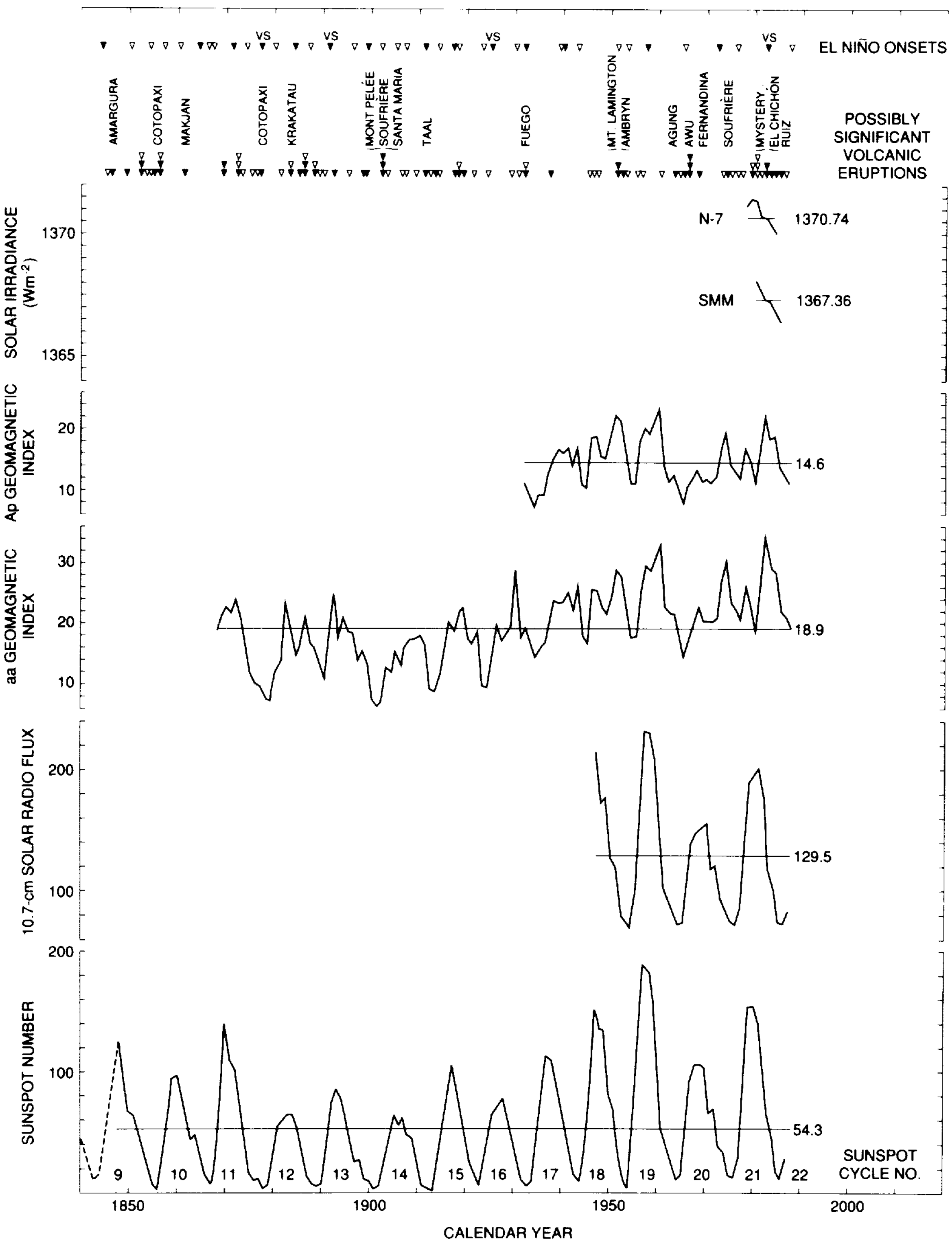

Figure 1. Annual counts of El Niño in relation to annual counts of possibly significant volcanic eruptions and to annual averages of sunspot number, 10.7-cm solar radio flux, aa and Ap geomagnetic indices, and solar irradiance (Nimbus 7 and Solar Maximum Mission) for the interval 1840-1987. Very strong (VS) El Niño events are denoted, as are several of the major volcanic eruptions (by name). Long-term averages are identified. See text for other details.

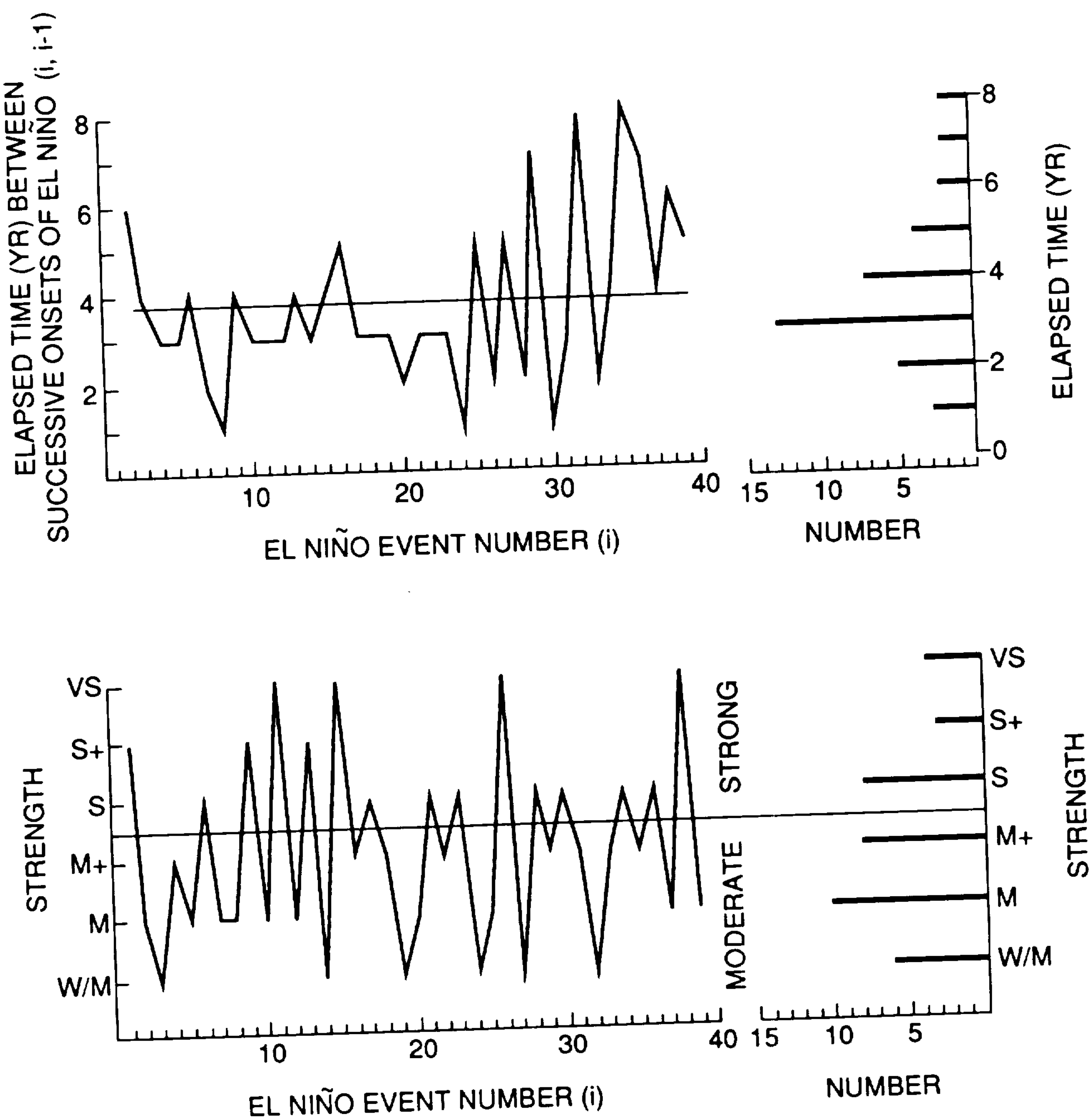

Figure 2. Elapsed time (in years) between successive onsets of moderate to stronger El Niño versus El Niño event number (i) during the interval 1840-1987 (top-left); the distribution of elapsed times (top-right); strength of El Niño versus El Niño event number (bottom-left); and the distribution of El Niño strengths (bottom-right).

although greater variation is clearly evident from about event number 23 (1917) than before it. Subdividing the events into two equally sized samples (2 to 20 and 21 to 39), one finds that the earlier occurring group (2 to 20) has a mean elapsed time of 3.3 years and a standard deviation of 1.1 years, while the more recently occurring group (21 to 39) has a mean elapsed time of 4.2 years and a standard deviation of 2.2 years. Hypothesis testing, based on the t statistic for independent samples (Lapin [155], p. 486) and assuming each sample to be normally distributed, suggests that the two samples are not significantly different, implying that the two groups can be combined into a single grouping and that a single mean and standard deviation can be used to describe the overall set of elapsed times. (It should be noted, however, that the sample containing events 2 to 20 has elapsed times spanning from 1 to 6 years, including a strong peak at 3 years, while the sample containing events 21 to 39 has elapsed times spanning 1 to 8 years, including a less striking peak at 3 years. Thus, while the former sample has a distribution that looks like the normal distribution, the latter sample's distribution does not; instead, it has a distribution more like that of the uniform distribution. Also, because greater variance exists in the latter sample as compared to that of the former sample — the variance of the sample comprised of events 21 to 39 is four times larger than the variance of the sample comprised of events 2 to 20 — one speculates that a change to a more variable climate may have occurred during the present century, especially the last 50 to 75 years. If true, one wonders whether the change is merely a natural episodic swing in climate or is it an anthropogenic effect?)

Also plotted in Figure 2 (top-right) is the overall distribution of elapsed times, making no distinction between events 2 to 20 and 21 to 39. Because the mode and median are smaller than the mean, one perceives that the distribution is positively (or rightward) skewed. Application of the Kolmogorov-Smirnov maximum deviation test for goodness of fit (Lapin [155], p. 639), using an assumed value of 3.5 years and 2.0 years, respectively, for the mean and standard deviation of the population of elapsed times, suggests that the distribution of elapsed times is normally distributed; on the other hand, a population mean and standard deviation of 4.0 years and 2.0 years, respectively, suggests that the distribution of elapsed times may not be normally distributed. (The distribution of elapsed times for the entire sample, as shown in Figure 2, certainly looks normally distributed; based on a sample distribution of 38 elapsed times, having a sample mean of 3.7 years and a sample standard deviation of 1.8 years, one computes the population mean and standard deviation to be $\mu = 3.7 \pm 0.6$ and $\sigma = 1.8 \; {+0.6}/{-0.3}$, respectively, at the 95 percent level of confidence.)

The above analysis suggests that El Niño events of moderate to stronger strength do not occur on an annual basis. Instead, they usually occur about once every 3 years (one-third of the entire sample; two-thirds of the entire sample have elapsed times of 2 to 4 years) and only occasionally do they occur in back-to-back years (elapsed time equals 1 year which is observed in only about 8 percent of the sample). Elapsed times between onsets of El Niño that exceed 5 years have been more commonplace of late than was evident early on, with 5 of the 6 events occurring in the last 50 years. Because the onsets of El Niño usually occur after the Earth's closest approach to the Sun when insolation is greatest, one supposes that insolation should be a major factor in the genesis of El Niño; however, because of the lack of an annual signal in the elapsed times between successive El Niño of moderate to stronger intensity, one surmises that insolation alone cannot fully explain the observed variation. (El Niño events usually have their onsets during southern hemispheric summer/fall, corresponding to December-May; a comparison of the events listed in Table 1 to those identified in Deser and Wallace [52] for the interval 1925 to 1986 shows that more than 80 percent of the El Niño events had their onsets during southern hemispheric summer/fall, with the greatest number during southern summer and with no events during southern winter—June-August.

It should also be noted that an annual signal occurs in the 10.7-cm solar radio flux, which is a consequence of the Earth's orbital motion, being higher, on average, during January than during July, and a semiannual signal occurs in geomagnetic activity, which may be a consequence of the tilt of the Sun's rotational axis relative to the equator, with enhanced geomagnetic activity in March and September, when more of the Sun's polar regions face the Earth, than in June and December.)

Also plotted in Figure 2 (bottom-left and bottom-right, respectively) is the time variation of the relative strengths of the moderate to stronger El Niño events and their distribution. Although the strengths appear to vary randomly, moderate El Niño events occur more often than strong El Niño events and the time series of El Niño strengths has, as yet, never included a strong-strong occurrence. Thus, if one were forecasting the relative strength for the "next" El Niño, one probably would forecast a moderate event, especially if the last known event was a strong El Niño; on the other hand, if the last event was a moderate event, one could only say that the next anticipated event will be of moderate to stronger strength (ignoring the weaker El Niño events).

B. El Niño Onsets Versus Volcanic Activity

More than 200 years ago, Benjamin Franklin [72] noted a coolness during the summer months of 1783 that was associated with a "constant fog" over Europe and North America. According to Franklin, surface temperature decreased because some of the incident sunlight could not reach the Earth's surface, owing to the presence of the fog. Of several possible causes for the fog, Franklin speculated that volcanic activity in Iceland might be responsible for the meteorological effects [23, 50, 215, 254, 261].

Later, Humphreys [121] showed that preferential scattering of sunlight by volcanic aerosols could alter the Earth's albedo, thereby effecting climatic changes (cf. Humphreys [122]), and Kimball [139-140] showed that reduction in the amount of direct sunlight at the Earth's surface by as much as 20 to 30 percent of that ordinarily observed was seen after certain volcanic eruptions [190, 290-291]. In 1961 a persistent, world-wide, stratospheric aerosol layer, composed mainly of sulfate particles (and sulfuric acid droplets), was detected by high-altitude balloon and aircraft sampling experiments [22, 129-130]. Results of monitoring this layer have since shown that direct volcanic injection occasionally takes place, having both immediate short-term and severe longer term effects [79, 181]. As an example of a possible climatic effect related to volcanic eruptions, Kondo [143] has noted that "most of the poor rice harvests caused by unusual cool summers and leading famine conditions in the Tohoku district (the northeastern part of Japan) took place just after the great volcanic eruptions" during the last 300 years (cf. [19, 94-96, 163, 188, 196, 202]). It is perceived, then, that volcanic eruptions, especially violent ones in the tropics, because of their globally perturbing aerosols (Lamb [154]), alter the Earth's atmospheric circulation, thereby, influencing both local and world-wide climatology [5-6, 30-32, 46-47, 53, 58-59, 76, 82-83, 97, 100, 111, 113, 118, 120, 123, 127, 133-134, 150, 152, 159, 164, 170-172, 175, 182, 184-185, 187, 191, 193, 197, 203-204, 214, 223, 229-230, 235, 239-243, 245, 255-256, 258, 266, 269, 281-283, 312].

Recently, Handler [94-95] examined the relationship between El Niño occurrences and volcanic eruptions, to determine whether or not the 1982-83 El Niño was related to the March-April 1982 eruptions of El Chichón. In his analysis, he composited (using the superposed epoch analysis technique; cf. Haurwitz and Brier [103]) separately and seasonally the SST's for 11 low-latitude (≤20 degrees) and 20 high-latitude (>20 degrees) eruptions occurring between 1868 and 1980, where the SST's were for the eastern equatorial Pacific bounded by 0 to 10°S and 90 to 180°W. His results suggest that, when major stratospheric aerosols occur at low latitudes, the SST's of the eastern equatorial Pacific tend to be warmer than normal for the three seasons following the eruptions and that, when major stratospheric aerosols occur at high latitudes, the SST's tend to be cooler than normal for about four or five seasons following the eruptions, concluding that the association between SST anomalies and volcanic eruptions is statistically significant at the 95 percent level of confidence.

While Parker [202], using a different data set, has confirmed Handler's findings, Nicholls [196] notes that, in composites (10 events) of Darwin SLP, another measure often employed to indicate the occurrence of El Niño, the date of eruption tends to be preceded by lower than average pressure and followed by higher than average pressure. He further found that "a strong linear upward trend in the composite pressure anomaly starts well before the date of eruptions and continues for several months" afterward, suggesting that ENSO events do not result from low-latitude volcanic eruptions (owing to violation of causality). Similar conflicting results can be found in Sear and Kelly [257] both for individual and composited events based on northern hemisphere air temperature (cooling is seen to have begun some 3 months prior to the El Chichón eruption and 5 months prior to the dates of eruption based on a composite of five eruptions).

To assess the associational aspects of El Niño and volcanic eruptions, from Figure 1, one can compare the onsets of El Niño with the occurrences of volcanic eruptions. From the preceding, if a strong association exists between volcanic eruption in the tropics (cause) and the onset of El Niño (effect), then one expects volcanic eruptions to preferentially occur before (or simultaneously with) the appearances of El Niño, because the response should be essentially immediate with only slight delay (within three to five seasons; certainly, within 2 years). (Observations of the decay of the aerosol load following selected eruptions indicate that it has an e-folding time of about 1 year, implying that the original load has been reduced by about a factor of 2.7, 1 year after the eruption, by about 7.4, 2 years after the eruption, and by about 20.1, 3 years following the eruption. Also volcanic materials have been observed to circumnavigate the globe in less than 1 month and to span from pole to pole in about 1 year, with the maximum opacity usually occurring within the hemisphere of origin and in less than 1 year following the eruption.)

Figure 3 plots the results of a comparison of occurrences of volcanic eruption relative to El Niño onsets for tropical volcanic eruptions alone (bottom) and for "all" major volcanic eruptions (ignoring the latitudinal position of the eruptions; top). If El Niño events result purely from the eruptions of major low-latitude (tropical) volcanoes that precede the onsets of El Niño by ≤ 1 year (within seven seasons), one finds that only 16 out of 38 El Niño events (between 1848 and 1987) can possibly be "explained." If one opens the window to include all major tropical eruptions within 2 years (within 11 seasons), then one finds that the supposed association can only account for 22 out of 38 El Niño onsets (about 60 percent). Thus, nearly half (≥ 40 percent) of the El Niño onsets are not preceded (within 2 years) by a major volcanic eruption in the tropics.

From Figure 3 (top), if one ignores the location of the volcanic eruption, one finds a stronger apparent association between them. For example, within 1 year, 26 out of 38 El Niño onsets were preceded by a major eruption and, within 2 years, 30 out of 38 El Niño onsets were preceded by a major eruption; only 8 out of 38 (about 20 percent) were not preceded by a major eruption. Thus, by ignoring latitude, one can attribute more of the El Niño events to the occurrences of major volcanic eruptions; however, the association does not appear to be one-to-one. (It should be emphasized that this analysis was performed relative to El Niño onset.)

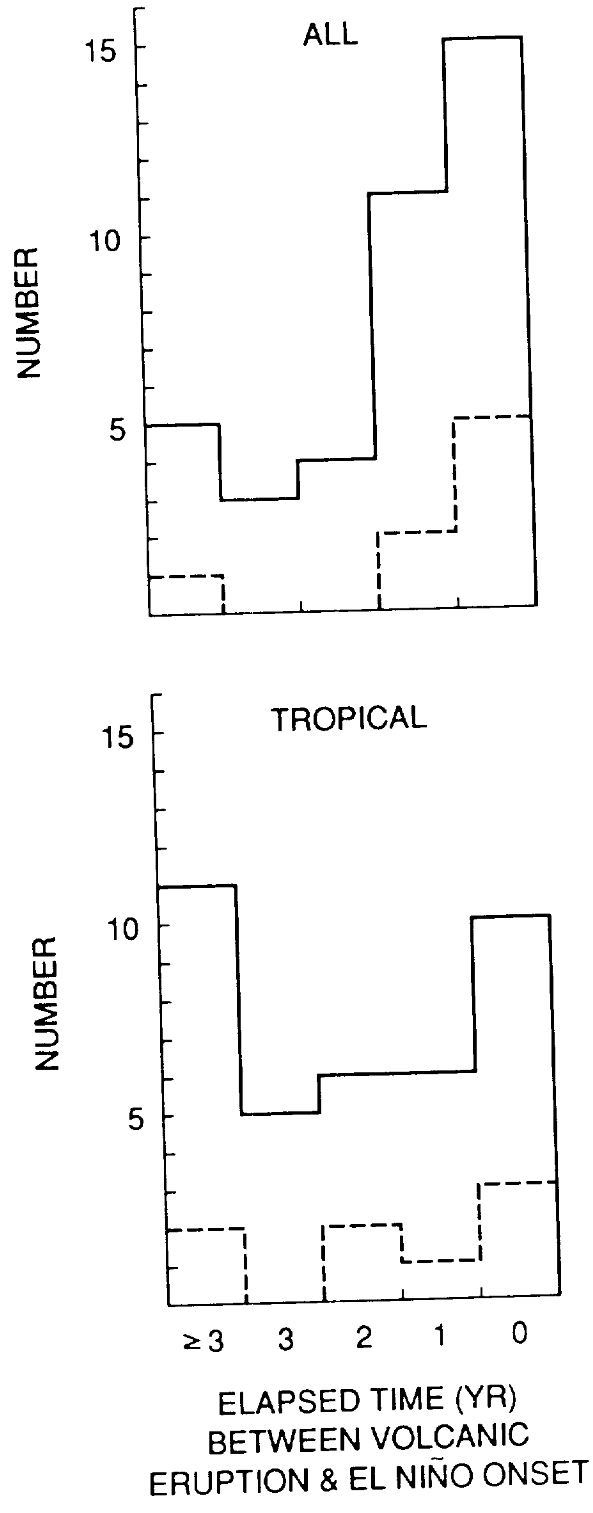

Figure 3. A histogram depiction of the number of El Niño events of moderate to stronger strength versus elapsed time (in years) between onsets of El Niño and the preceding tropical (bottom) and latitude-independent (denoted "All;" top) major volcanic eruptions. The dashed lines refer to events occurring since 1950.

Limiting oneself to just those events that have occurred since 1950 (8 events, the dashed lines in Figure 3), one finds that 6 out of 8 El Niño onsets were preceded (within 2 years) by major volcanic eruptions in the tropics, or that the association is roughly in the same proportion as that of the larger comparison. Ignoring latitude, one finds 7 out of 8 El Niño onsets to be preceded (within 2 years; actually within 1 year) by major volcanic eruptions. Thus, although the more reliable data set indicates a possible connection between El Niño onsets and preceding major volcanic eruptions, the inferred association remains not one-to-one. Event 36 (Table 1), the strong El Niño of 1972-73, cannot be attributed to any known major volcanic eruption ($\leq$3 years), regardless of latitude.

Table 3 lists the possible associations that may exist between El Niño onsets and major, low-latitude (tropical) volcanic eruptions for elapsed times spanning 0 to 3 years. It identifies the particular El Niño event, its onset year and strength, and the name, location, VEI (if known; otherwise the DVI is given), and month of eruption for the possibly associated volcano. As previously noted in the discussion of Figure 3, 10 El Niño onsets occur during the same years of the occurrences of major, tropical volcanic eruptions. Of these 10, 8 occur during the first part of the year when El Niño is usually observed; two eruptions occur late in the year making these associations less likely. These two events are numbers 17 and 35. Instead of same year occurrence for both the El Niño and the eruption for these two events, event 17 may be better associated with the eruption of Una Una (0°S) in 1898, implying an elapsed time of 1 year, and event 35 may be better associated with the eruption of Gunung Agung (8°S) in March 1963, implying an elapsed time of 2 years.

Table 4 identifies all of the extratropical, southern hemispheric eruptions (6) that occurred prior to the onsets of El Niño. While it is less likely that these eruptions produced stratospheric aerosols that were global in extent (the adage is that extratropical eruptions tend to be most effective within their hemisphere of origin, while tropical eruptions can be effective throughout the tropics, even globally; Lamb [154]; Dyer [58]), they should have produced aerosols that were effective in the southern hemisphere. Combining the results of Tables 3 and 4, one finds that, if El Niño can be triggered by preceding (within 2 years) major, tropical and/or extratropical (southern hemisphere) volcanic eruptions, then such an association can only account for about two-thirds of the observed El Niño (25 out of 38 events); one-third must be triggered by something else. As has been previously noted, the association appears stronger if one disregards latitude; likewise, by including smaller eruptions (VEI $\leq$3), one also can infer a stronger association.

C. El Niño Onsets Versus Solar/Geomagnetic Activity

Two examples of solar-terrestrial relationships are the distribution of average air temperature from the equator to the pole (warmer near the equator as compared to cooler near the poles) and the existence of aurorae, the implication being that a changing Sun is, perhaps, a major piece of the puzzle regarding weather/climate. While the Sun is recognized as the ultimate source of energy for the atmospheric-oceanic climatic system, because a full understanding of the step-by-step processes at work within the system has not yet been realized, researchers remain cautious, even skeptical, towards any claims as related to Sun-weather/climate.

TABLE 3. SUMMARY OF EL NIÑO EVENTS THAT POSSIBLY MAY BE ASSOCIATED WITH LOW-LATITUDINAL (TROPICAL) VOLCANIC ERUPTIONS

Event	Onset	Strength	Volcano	Latitude	VEI	Month
Elapsed time (year) = 0						
11	1877	VS	Cotopaxi	1 S	4	June
17a	1899	S	Doña Juana	2 N	4	November
18	1902	M +	Santa Maria	15 N	6	May
			Soufrière	13 N	4	May
			Mont Pelée	15 N	4	May
21	1911	S	Taal	14 N	4	June
23	1917	S	Agrigan	19 N	4	April
24	1918	W/M	Tungurahua	1 S	4	April
28	1932	S	Fuego	14 N	4	January
32b	1951	W/M	Ambryn	16 S	4	September
			Mt. Lamington	9 S	4	January
35c	1965	M +	Taal	14 N	4	September
38	1982	VS	El Chichón	17 N	4	April

a. Possibly better associated with Una Una (Lat. 0 S) which erupted in 1898.
b. Possibly better associated with Mt. Lamington than Ambryn.
c. Possibly better associated with Gunung Agung (Lat. 8 S) which erupted in March 1963.

Event	Onset	Strength	Volcano	Latitude	VEI	Month
Elapsed time (year) = 1						
2	1850	M	Purace	2 N	4	December
4	1857	M +	Sangihe	4 N	(DVI = 500?)	March
			Awu	4 N	(DVI = 70)	?
			Cotopaxi	1 S	(DVI = 700)	?
13	1884	S +	Krakatau	6 S	6	August
14a	1887	W/M	Niafu	16 S	(DVI = 300)	?
			Tungurahua	1 S	4	June
22	1914	M +	Colima	19 N	4	June
33	1953	M +	Bagana	6 S	4	February

a. Tarawera (38 S) erupted in June 1886, having VEI = 5.

TABLE 3. (Concluded)

Event	Onset	Strength	Volcano	Latitude	VEI	Month
Elapsed time (year) = 2						
3	1854	W/M	Gunung Api	4 S	(DVI = 200) ?	
9	1871	S+	Purace	2 N	4	October
10	1874	M	Merapi	8 S	(DVI = 80)	April
29	1939	M+	Rabual	5 S	4	May
37	1976	M	Fuego	14 N	4	October
39	1987	M	Ruiz	5 N	a	November

a. Dust cloud possibly to 25 km.

Event	Onset	Strength	Volcano	Latitude	VEI	Month
Elapsed time (year) = 3						
6	1864	S	Makjan	0 N	(DVI = 800)	December
12	1880	M	Cotopaxi	1 S	4	June
15	1891	VS	Ritter Island	6 S	(DVI = 250) ?	
19	1905	W/M	Santa Maria	15 N	6	May
			Soufrière	13 N	4	May
			Mont Pelée	15 N	4	May
30	1940	S	Rabual	5 S	4	May

TABLE 4. MID-TO-HIGH LATITUDE SOUTHERN HEMISPHERE VOLCANIC ERUPTIONS THAT POSSIBLY MAY BE ASSOCIATED WITH EL NIÑO EVENTS

Year	Volcano	Latitude	VEI	Month	Event	Year	Strength
1886	Tarawera	38 S	5	June	14	1887	W/M
1895/96	Thompson Island	54 S	(DVI = 1300)	?	16	1896	M+
1921	Puyehue	41 S	4	December	25	1923	M
1932	Quizopu	36 S	6	April	28	1932	S
1955	Nilahue	40 S	4	July	34	1957	S
1960	Puntiagudo	42 S	(DVI = 100)	May	35	1965	M+

One of the first in this century to suggest a connection between the Sun and terrestrial weather/climate was Humphreys [120], who also related the production of terrestrial ozone to solar ultraviolet (UV) radiation and to auroral discharge. Variations over the solar cycle of the UV flux, the solar constant, and the geomagnetic activity (related to the occurrences of solar flares, coronal holes, erupting prominences, and even the time of year) have been documented which have been associated, in particular, with changes in the upper and middle atmospheres and, possibly, with changes even in the lower atmosphere, although it is this latter aspect that is often controversial [2-4, 10, 17, 21, 24-26, 33, 42-45, 49, 54-57, 73, 75, 77, 81, 84-85, 90, 102, 104-105, 107-109, 115, 126, 131-132, 141-142, 144, 149, 151, 169, 177, 179, 186, 198-200, 205, 211-213, 217-219, 236-237, 250-251, 253, 259, 263-265, 268, 270-271, 277, 279-280, 293-297, 312, 324].

The term "solar activity cycle" (or solar cycle) is the general term employed to describe the multiplicity of solar-related phenomena that appear to vary cyclicly in a periodic or quasi-periodic manner, having a period of approximately 11 (or 22) years. The oldest measure of the solar cycle is the relative sunspot number first introduced by Rudolf Wolf in 1848 (cf. Waldmeier [285]; Kiepenheuer [137]; Wilson [299]; McKinnon [176]). Other measures include, for example, the 10.7-cm solar radio flux, sunspot area, photospheric line strengths, number of sunspot groups, number of sunspots, number of solar flares, etc. In a larger sense, the solar cycle includes not only the sunspot cycle, but also variations of the solar irradiance (which is believed to vary over the sunspot cycle; e.g., Hudson [119]; Livingston, Wallace, and White [161]; Willson and Hudson [298]) and the geomagnetic cycle (since the magnetic disturbances that give rise to the fluctuations, especially as seen in the aa and Ap indices, are believed to be streams of charged particles of solar origin; cf. Garland [78]; Feynman and Gu [68]; Mavromichalaki, Vassilaki, and Marmatsouri [165]). Provided that statistically significant correlations exist between the various parameters and sunspot number, one can use the sunspot cycle as a proxy for the solar cycle, thereby allowing a convenient way to assess statistical aspects of El Niño, especially those that might be suggested as being indicative of preferential behavior.

Scatter plots of solar irradiance (from Nimbus 7 and Solar Maximum Mission), geomagnetic indices (aa and Ap), and the 10.7-cm solar radio flux against sunspot number (using annual averages) are shown in Figure 4. In each case the depicted linear fit is found to be statistically significant, although considerable variation is seen in the geomagnetic indices. On the basis of these linear fits, one infers that, indeed, the various parameters are directly correlated with sunspot number. Thus, sunspot number (the sunspot cycle) can be used as a proxy for the solar/geomagnetic cycles and for the study of statistical associations between onsets of El Niño and the solar cycle. Statistically speaking, one infers that >80 percent of the variation observed in the 10.7-cm solar radio flux can be "explained" by the variation observed in sunspot number, while >90 percent of the observed variation in the solar irradiance as measured by the Solar Maximum Mission can be explained by the variation observed in sunspot number. The percentage of explained variation is about 20, about 30, and about 50 percent for the Ap index, the aa index, and the solar irradiance as measured by the Nimbus 7, respectively.

The results of superposed epoch analyses, using sunspot minimum occurrence as the epoch of comparison, are illustrated in Figure 5 for Ap, aa, 10.7-cm solar radio flux, and sunspot number. As noted above, the geomagnetic indices, the 10.7-cm solar radio flux, and sunspot number all display a somewhat cyclic appearance, having a period of about 10 to 11 years and a maximum about midway through the cycle. More specifically, while sunspot number and 10.7-cm solar radio flux have minima that coincide exactly, Ap and aa minima usually follow sunspot minimum by about 1 year. For Cycles 18 and 19, maxima in sunspot number and 10.7-cm solar radio flux coincide exactly, while for Cycles 20

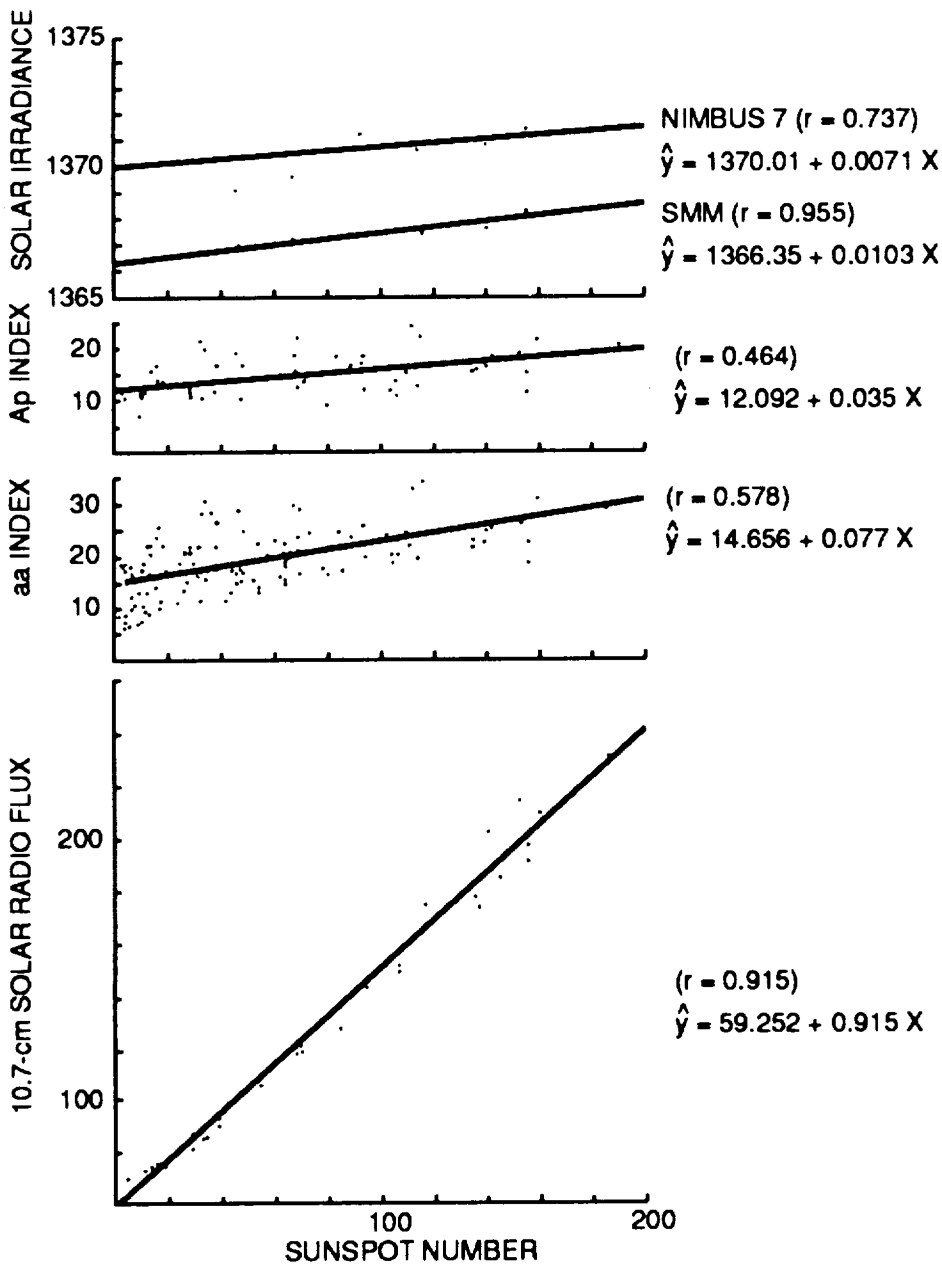

Figure 4. Linear fits of 10.7-cm solar radio flux, aa, Ap, and solar irradiance (Nimbus 7 and Solar Maximum Mission) against sunspot number using annual averages of each. The linear regressions are shown as are the correlation coefficients (r).

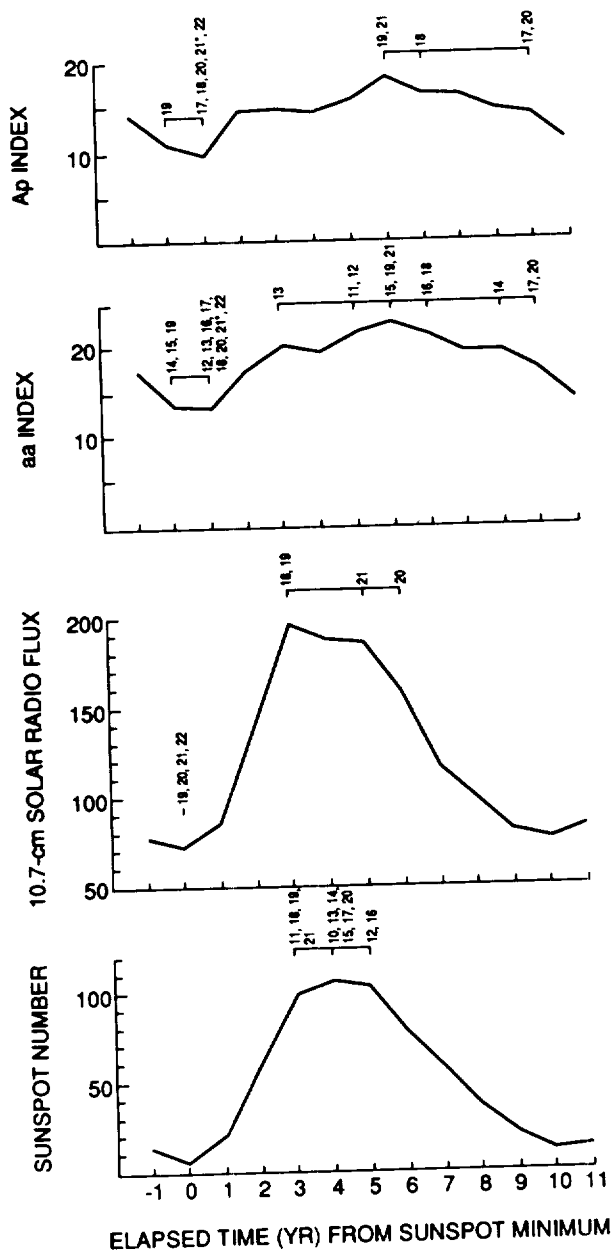

Figure 5. Superposed epoch analyses of sunspot number, 10.7-cm solar radio flux, aa, and Ap based on the epoch of sunspot number minimum (using annual averages). Individual cycle minima and maxima are identified for each parameter. The asterisk (*) shown for Cycle 21 indicates that for both aa and Ap, a minimum occurred at the relative position shown; however, the lowest minimum occurred in 1980, near sunspot maximum, unlike any previous cycle.

and 21 the radio flux maximum followed the sunspot number maximum by about 2 years. Maxima in the two geomagnetic indices have always coincided with each other (as have their minima), and they have almost always followed their respective sunspot maxima by two or more years with only two exceptions: In Cycle 12 the maxima for both sunspot number and the geomagnetic indices coincided and in Cycle 13 the geomagnetic maximum preceded the sunspot maximum by 1 year. Sunspot maximum has always followed sunspot minimum by 4 ± 1 year for the most reliably known sunspot cycles, and the 10.7-cm solar radio flux maximum has always followed its minimum by 3 to 6 years. The difference in epochs of maximum for sunspot number and the 10.7-cm solar radio flux appears to be related to how they track the number of sunspot groups and the number of individual sunspots observable on the Sun's disk, with sunspot number being more heavily influenced by the number of groups and with the 10.7-cm solar radio flux being more heavily influenced by the number of observed sunspots [308]. Geomagnetic activity, on the other hand, does not generally peak until after sunspot maximum (during the decline of the sunspot cycle), although it is at elevated levels from about 2 to 3 years into the cycle until about 9 to 10 years into the cycle (Cycle 21 was unusual in that, while a minimum in the geomagnetic indices occurred about 1 year after sunspot minimum, the "true" minimum occurred in 1980, or near sunspot maximum; geomagnetic maximum occurred in 1982, being the largest ever recorded in terms of the aa index). Because the geomagnetic indices may be related to the solar wind speed [48, 67-68], solar wind speed is inferred to be greater, on average, after sunspot maximum (probably associated with the corotating, high-speed, solar wind streams that are spawned from coronal holes [147, 325]).

Now, having established that the sunspot cycle can serve as proxy for the solar cycle (and the 10.7-cm solar radio flux, the geomagnetic cycle, and solar irradiance), with the caveats as noted, one can compare onsets of El Niño with various markers of the sunspot cycle (e.g., average sunspot number, epochs of minimum and maximum, rise and fall, etc.) to search for possibly significant statistical associations. From Figure 1, one finds that more El Niño events (ignoring intensity) had onsets when the annual sunspot number was below average (54.3) than when sunspot number was above average; in particular, 24 out of 38 El Niño events had onsets when sunspot number was below 54.3, and of the 24 events associated with below average annual sunspot number, 17 were of moderate intensity (Table 5).

TABLE 5. NUMBER OF EL NIÑO EVENTS IN RELATION TO THE MEAN ANNUAL SUNSPOT NUMBER (= 54.3), BASED ON THE MODERN ERA SUNSPOT OBSERVATIONS (1848-1987)

El Niño (Intensity)	Below (<54.3)	Above (≥54.3)	Total
W/M	3	3	6
M	7	3	10
M+	7	1	8
(Subtotal)	(17)	(7)	(24)
S	4	4	8
S+	0	2	2
VS	3	1	4
(Subtotal)	(7)	(7)	(14)
Total	24	14	38

While true, these results should not really be surprising, because for 80 years of the 140-year modern era sunspot record the annual sunspot number was below 54.3. Therefore, by chance, one infers that 22 events should have had onsets when the annual sunspot number was below 54.3 (ignoring intensity), of which 14 should have been of moderate intensity. From the binomial formula (Lapin [155], p. 163) and using a trial success probability of 80/140 (= 0.571), one easily calculates the probability of obtaining the observed results, or those more suggestive of a departure from independence (chance), to be $P[\geq 24] = 27.9$ percent and $P[\geq 17] = 12.3$ percent, respectively, and by hypothesis testing, because $P[\geq 24]$ and $P[\geq 17]$ are both >10 percent, one infers that the association between the number of onsets of El Niño and below average annual sunspot number and between the number of onsets of moderate El Niño and below average annual sunspot number, in each case, is statistically unimportant (i.e., the difference between 24 and 22 events and between 17 and 14 events can, in both cases, be attributed entirely to chance).

The above analysis was based on a comparison of numbers of El Niño events and the average annual sunspot number. Instead, if one uses for comparison the "median" annual sunspot number (= 45.3), implying a trial success probability of 0.5, then one finds that 23 El Niño events had their onsets when annual sunspot number was below the median value annual sunspot number, of which 17 were of moderate intensity. From the binomial formula, one now calculates $P[\geq 23] = 12.8$ percent and $P[\geq 17] = 3.2$ percent, the first of nearly marginal statistical significance and the second statistically significant at >95 percent level of confidence. Comparing the numbers of onsets of El Niño (by strength) against the median value of annual sunspot number (i.e., the Fisher's test for a 2×2 table; Everitt [65], p. 15), one finds that a marginally significant association appears to exist between the strength of El Niño and sunspot number, with moderate El Niño favoring the time when annual sunspot number is below its median value and with strong El Niño favoring the time when annual sunspot number is above its median value ($P = 8.8$ percent). Table 6 and Figure 6 summarize these results.

In Table 7, the number of El Niño onsets is determined relative to whether the sunspot cycle is rising (minimum to maximum) or falling (maximum to minimum). From Table 7, one finds that 27 out of 38 El Niño events had onsets during the falling (or declining) portion of the sunspot cycle. By chance, one would have expected 24 events (= $38 \times 7/11$; a sunspot cycle, on average, lasts 11 years, taking 4 years to rise from minimum to maximum and 7 years to fall from maximum to subsequent cycle minimum). Applying the binomial formula, one computes $P[\geq 27] = 21.8$ percent, inferring that the association between the number of El Niño onsets and the phase of the solar cycle (in particular, the falling portion of the sunspot cycle) is statistically unimportant (i.e., the difference between 27 and 24 events can be attributed entirely to chance).

In contrast to that reported above, a possibly significant statistical association is found between the number of strong El Niño and the falling portion of the sunspot cycle. From Table 7, one sees that 12 out of 14 strong El Niño events had onsets during the falling portion of the sunspot cycle. By chance, one expects only 9 events. Applying the binomial formula, one computes $P[\geq 12] = 6.9$ percent, a marginally significant result (i.e., at about the 93 percent level of confidence, one infers that the difference between 12 and 9 events cannot be attributed to chance).

Table 8 compares the occurrences of El Niño onsets to the occurrences of sunspot minimum and maximum (actually, a window of ±1 year bounding each sunspot minimum and maximum). One finds that during the 3-year window of sunspot minimum, 11 El Niño of moderate intensity had their onsets, as did two strong El Niño (one of which was classified "very strong"); during the 3-year window

TABLE 6. NUMBER OF EL NIÑO EVENTS FOR ABOVE/BELOW MEDIAN ANNUAL SUNSPOT NUMBER (= 45.3) INTERVALS (1848-1987)

Interval	Years	Duration	Above/Below	Moderate	Strong	Total
1	1848-52	5	A	1		1
2	1853-57	5	B	2		2
3	1858-62	5	A	1		1
4	1863	1	B			
5	1864	1	A		1	1
6	1865-68	4	B	2		2
7	1869-73	5	A		1	1
8	1874-80	7	B	2	1	3
9	1881-85	5	A		1	1
10	1886-91	6	B	1	1	2
11	1892-95	4	A			
12	1896-1904	9	B	2	1	3
13	1905-08	4	A	2		2
14	1909-14	6	B	1	1	2
15	1915-19	5	A	1	1	2
16	1920-25	6	B	1	1	2
17	1926-29	4	A			
18	1930-35	6	B	1	1	2
19	1936-41	6	A	1	1	2
20	1942-45	4	B	1		1
21	1946-51	6	A	1		1
22	1952-55	4	B	1		1
23	1956-61	6	A		1	1
24	1962-65	4	B	1		1
25	1966-72	7	A		1	1
26	1973-77	5	B	1		1
27	1978-84	7	A		1	1
28	1985-87	3	B		1	1
Totals	Above	70	14	7	8	15
	Below	70	14	17	6	23
	Combined	140	28	24	14	38

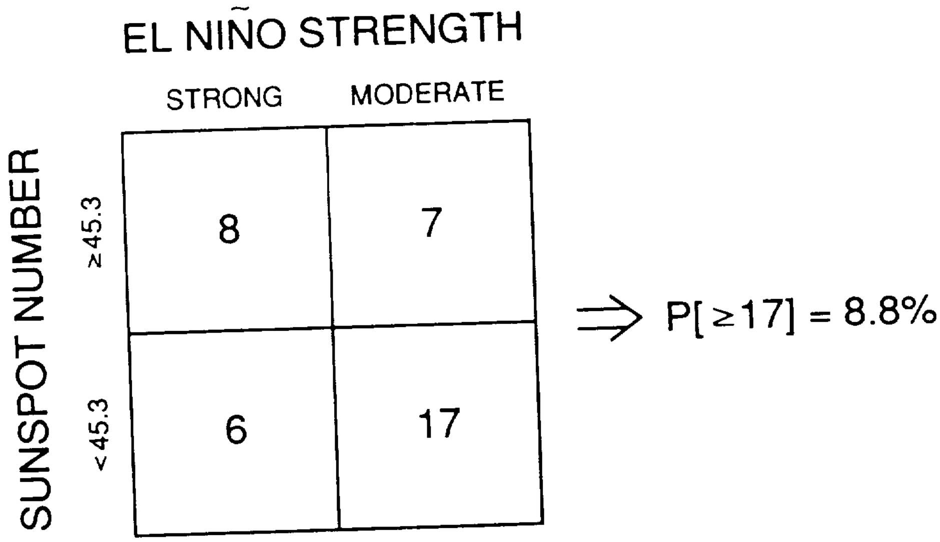

Figure 6. A 2 × 2 contingency table showing the association between annual sunspot number and number of El Niño events, dividing the events according to strength (moderate/strong) and median value (45.3). The probability of obtaining the observed result, or one more suggestive of a departure from independence, is P[≥17] = 8.8 percent, based on the Fisher's exact test for 2 × 2 tables.

TABLE 7. NUMBER OF EL NIÑO EVENTS IN RELATION TO THE RISE AND FALL OF THE SUNSPOT CYCLE, BASED ON THE MODERN ERA SUNSPOT OBSERVATIONS (1848-1987)

El Niño (Intensity)	Rise	Fall	Total
W/M	0	6	6
M	5	5	10
M+	4	4	8
(Subtotal)	(9)	(15)	(24)
S	0	8	8
S+	0	2	2
VS	2	2	4
(Subtotal)	(2)	(12)	(14)
Total	11	27	38

TABLE 8. NUMBER OF EL NIÑO EVENTS IN RELATION TO THE EPOCHS OF SUNSPOT MINIMUM AND MAXIMUM FOR CYCLES 10 TO 22

	Minimum (± 1 year)		Maximum (± 1 year)		
Cycle	Moderate	Strong	Moderate	Strong	Total
10	1		1		2
11	2			1	3
12		1(VS)		1	2
13	*				*
14	1		1		2
15	1		1	1	3
16	1				1
17		1			1
18	1				1
19	1			1	2
20	1				1
21	1				1
22	1		*	*	1*
(Subtotal)	(11*)	(2)	(3*)	(4*)	
Total	13*		7*		20*

NOTE: A moderate event is in progress during Cycle 13 at minimum (having begun 2 years prior to minimum); Cycle 22 maximum has not yet occurred.

of sunspot maximum, only three El Niño of moderate intensity had their onsets, as did four strong El Niño. Assuming a trial success probability of 0.5 for each group, one finds that the probability of obtaining 13 or more El Niño onsets (ignoring intensity) near sunspot minimum is P[≥13] = 13.2 percent and the probability of obtaining 11 or more moderate El Niño onsets near sunspot minimum is P[≥11] = 2.9 percent. Comparing the number of El Niño onsets near sunspot minimum against the remainder of the sunspot cycle, one finds that the probability of obtaining 13 or more El Niño onsets (ignoring intensity) near sunspot minimum is P[≥13] = 21.5 percent and the probability of obtaining 11 or more moderate El Niño onsets near sunspot minimum is P[≥11] = 4.0 percent. Thus, a possibly significant statistical association is found for moderate El Niño events to have their onsets near sunspot minimum (at ≥96 percent level of confidence). Using only El Niño events with onsets in the windows of sunspot minimum and maximum (a 2 × 2 contingency table), one finds a tendency for moderate El Niño to associate with sunspot minimum and strong El Niño to associate with sunspot maximum (P = 7.8 percent, see Fig. 7).

A cycle-by-cycle listing of El Niño onsets (by intensity) is given in Table 9, which also identifies the maximum amplitude (size) of the cycle in terms of the annual sunspot number. Dividing the ensemble into two equally sized groups (removing Cycles 9 and 22 because they are only partially complete), Cycles 10 to 15 and 16 to 21, one finds that the average number of El Niño events (ignoring intensity) has decreased. Cycles 10 to 15 averaged 3.50 El Niño onsets per sunspot cycle (having a standard deviation of 0.55), while Cycles 16 to 21 averaged 2.33 El Niño onsets per sunspot cycle (having a standard deviation of 1.03). Hypothesis testing, using the t statistic for independent samples, suggests that the difference in the two means is statistically significant at ≥99.5 percent level of confidence. Thus, the number of El Niño onsets per sunspot cycle was greater during Cycles 10 to 15 (as compared to Cycles 16 to 21).

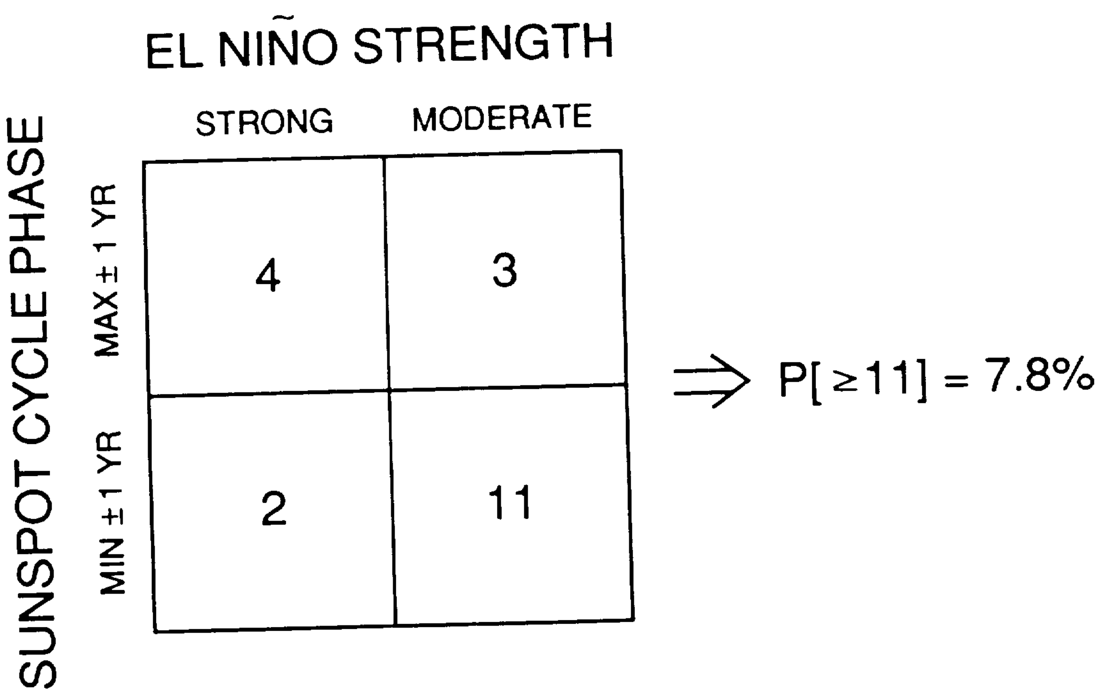

Figure 7. A 2 × 2 contingency table showing the association between sunspot cycle phase and number of El Niño events, dividing the events according to strength (moderate/strong) and epochs of sunspot minimum and maximum. The probability of obtaining the observed result, or one more suggestive of a departure from independence, is P[≥11] = 7.8 percent.

TABLE 9. NUMBER OF EL NIÑO EVENTS BY SUNSPOT CYCLE NUMBER DURING THE INTERVAL 1848-1987

Cycle	Rmax	El Niño Events (Intensity) W/M	M	M+	S	S+	VS	Total
9	124.7	1	1					≥2*
10	95.8		2	1	1			4
11	139.0		2			1	1	4
12	63.7	1	1			1		3
13	85.1			1	1		1	3
14	63.5	1	1	1	1			4
15	103.9	1		1	1			3
16	77.8	1	1		1		1	4
17	114.4			2	1			3
18	151.6	1		1				2
19	190.2				1			1
20	105.9			1	1			2
21	155.4		1				1	2
22	?		1					≥1*
Total		6	10	8	8	2	4	38*

*Note: Modern sunspot observations began about sunspot maximum during Cycle 9; consequently, the S+ El Niño (1844-45) near minimum has not been included in this summary; also, Cycle 22 (Rmax = ?) is only partially complete.

when maximum amplitudes tended to be smaller (larger). Application of Spearman's rank correlation test (Lapin [155], p. 633) suggests that the number of El Niño onsets per sunspot cycle may vary inversely with the size of the sunspot cycle at ≥95 percent level of confidence, having a Spearman rank correlation coefficient r_s equal to about -0.58 (implying that about one-third of the variation found in the number of El Niño onsets per sunspot cycle may be due to the relative size differences of sunspot cycles; it should be noted, however, that the inferred inverse correlation between number of El Niño onsets per sunspot cycle and the size of the sunspot cycle may be due simply to the "bimodality" of the sunspot cycle, a preferential division of the sunspot cycle into two separate groups according to period length: short-period cycles with a period <11 years and long-period cycles with a period >11 years, with short-period cycles, on average, being about 1.3 years shorter in duration than long-period cycles; cf. Rabin, Wilson, and Moore [224]; Wilson [300-302, 304]). The implication of this result (i.e., the inverse correlation) is that, because of the long-term secular increase in sunspot number (Wilson [303]), more El Niño events may have occurred during the Maunder minimum, a protracted period (1645 to 1715) of low sunspot number (Eddy [60-62]), than has been experienced of late, and that fewer El Niño events will occur in future sunspot cycles (modulated by the 80- to 100-year period or Gleissberg cycle; Kopecký [145]) and provided that the secular trend remains upward. From Quinn et al. [221], one finds some support for an inferred increase in El Niño activity during the Maunder minimum in that nine strong events occurred between 1652 and 1715, this number of strong events being about 50 percent higher than found for today's cycles. (Moderate events were tabulated by Quinn et al. only for the post-1800 time span.) One should also note that if the height of the tropopause really varies with the sunspot cycle, being lower near sunspot minimum than near sunspot maximum, then volcanic eruptions, perhaps even less violent ones of VEI ≤4, may more easily penetrate into the stratosphere, thereby initiating climatic change. This would seem to be especially so during prolonged periods of low sunspot activity like the Maunder minimum than during times of enhanced solar activity. Perhaps this may explain the greater frequency of strong El Niño during the Maunder minimum and of El Niño in general during the period of sunspot minimum that is seen.

D. Looking Ahead to the "Next" Anticipated El Niño

From a statistical point of view, El Niño appears, on average, about once every 3 to 4 years, having a range of 1 to 8 years. Assuming that the elapsed time between successive onsets of El Niño is normally distributed with a mean of 4 years and a standard deviation of 2 years, one anticipates an El Niño to occur usually within 2 to 6 years following the last known onset of El Niño, certainly within 8 years. Thus, looking at the 1982-83 El Niño as an example, one finds that an El Niño of moderate to stronger strength was expected about 1978 to 1982 from the 1976 last known occurrence of El Niño. From this perspective, one views the 1982-83 El Niño as an "expected" event. Similarly, having observed the onset of an El Niño in 1982, one expected the next El Niño to occur about 1984 to 1988 and, indeed, a moderate El Niño had its onset in 1987 (actually, in late 1986; Kousky [146]). Marking the last known El Niño onset as having occurred in 1987, one anticipates that another El Niño of moderate to stronger strength should make its appearance about 1989 to 1993, certainly by 1995.

A comparison of El Niño onsets in relation to major volcanic activity showed that about 40 percent of the El Niño events were preceded (within 1 year) by a major volcanic eruption in the tropics and that nearly 70 percent were preceded (within 1 year) by a major volcanic eruption somewhere in the world. If the amount of time between eruption (cause) and onset of El Niño (effect) is as long as 2 years, the inferred association appears even stronger: about 60 percent for major tropical eruptions and about 80 percent for any major eruption. Thus, a violent eruption of a volcano somewhere in the world often is found to herald the occurrence of a moderate to stronger El Niño (an exception may have been the 1972-73 El Niño, which followed the eruption of Fernandina by about 4 years). Such may have been the case for both the 1982-83 and 1987 El Niño events, in that both were preceded (within 2 years) by major volcanic activity. It follows, then, that if in the future, a major eruption takes place somewhere in the world, a moderate to stronger El Niño might be expected to follow within 2 years. Because major volcanic eruptions occur quite often, about once per 1.6 years (= 152 years/94 eruptions), in general, or about once per 2.1 years (= 152 years/73 grouped eruptions) for "grouped" (same year) eruptions, presuming that a major eruption occurs in 1989, one may anticipate the occurrence of the next moderate to strong El Niño during the period 1989 to 1991. (The range of elapsed times between major eruptions, based on Table 2, is 0 to 10 years.)

A comparison of El Niño onsets to various aspects of the solar/geomagnetic cycle also suggests a means whereby one might estimate the likelihood of an impending El Niño. For example, nearly two-thirds of the El Niño events had their onsets when sunspot number was <54.3 (the average annual sunspot number, based on the 1848 to 1987 observed values). Further, of the 24 that occurred when annual sunspot number was below 54.3, 17 were of moderate strength (or about 70 percent). Likewise, 27 (about 70 percent) El Niño events occurred after sunspot maximum during the decline of the cycle (when geomagnetic activity tends to be greatest) and 12 out of the 14 reported (about 85 percent) strong El Niño occurred post sunspot maximum. Regarding the epochs of sunspot minimum and maximum (± 1 year windows), one finds that about one-third of the El Niño events occurred near sunspot minimum (13 events, of which 11 were of moderate intensity) and that about 20 percent occurred near sunspot maximum (7 events, of which 4 were of strong intensity). The 1982-83 El Niño occurred about 6 years into Cycle 21, occurring during the same year as the peak of the geomagnetic activity (which, incidently, was the highest peak ever recorded, based on the aa geomagnetic index; the record high monthly value occurred in February 1982), and the 1987 El Niño occurred 1 year after sunspot minimum for Cycle 22. The year 1988 (2 years into the cycle) saw annual sunspot number surpass the average annual sunspot number value of 54.3, and it should remain above the average value until about 1993 (7 years into the cycle); peak sunspot activity is expected to occur about 1989 to 1991. Thus, the likelihood of another El Niño is, at present, increasing and will be especially high after sunspot maximum and also after a return to below average sunspot number. From Table 9, one recalls that, for Cycles 10 to 21, every sunspot cycle had at least one El Niño, with 3 to 4 events per cycle during Cycles 10 to 17 and only 1 to 2 events per cycle since Cycle 18 (which began in 1944). Cycles of late have been among the greatest on record (Cycles 19, 21, and 18 are the three largest sunspot cycles of the modern era, given here in descending order). It is now evident that Cycle 22 will also be a larger than average sized cycle (Wilson [304-307]). Therefore, one expects fewer than three El Niño events to occur during its course, of which one has already occurred (the 1987 event). It follows that only 1 to 2 events may remain to be seen during the current sunspot cycle, projected to end about 1996 to 1998. (Also from Table 9, one sees that every cycle during Cycles 10 to 21, except Cycle 18, had at least one strong El Niño; hence, because fewer than three El Niño events are expected for Cycle 22 and because one has already occurred, being of moderate strength, the next anticipated event may be of strong intensity.)

Figure 8 provides a visual summary for much of that just discussed, plotted in the form of histograms and plotted relative to the start of the sunspot cycle. On the bottom is a histogram of the onsets of the 39 El Niño events appearing in Table 1, with filled areas referring to strong El Niño events. Above the bottom panel is a histogram of the 94 occurrences of major volcanic eruptions (from Table 2), where filled areas refer to major eruptions in the tropics (the asterisks serve to note that the mystery

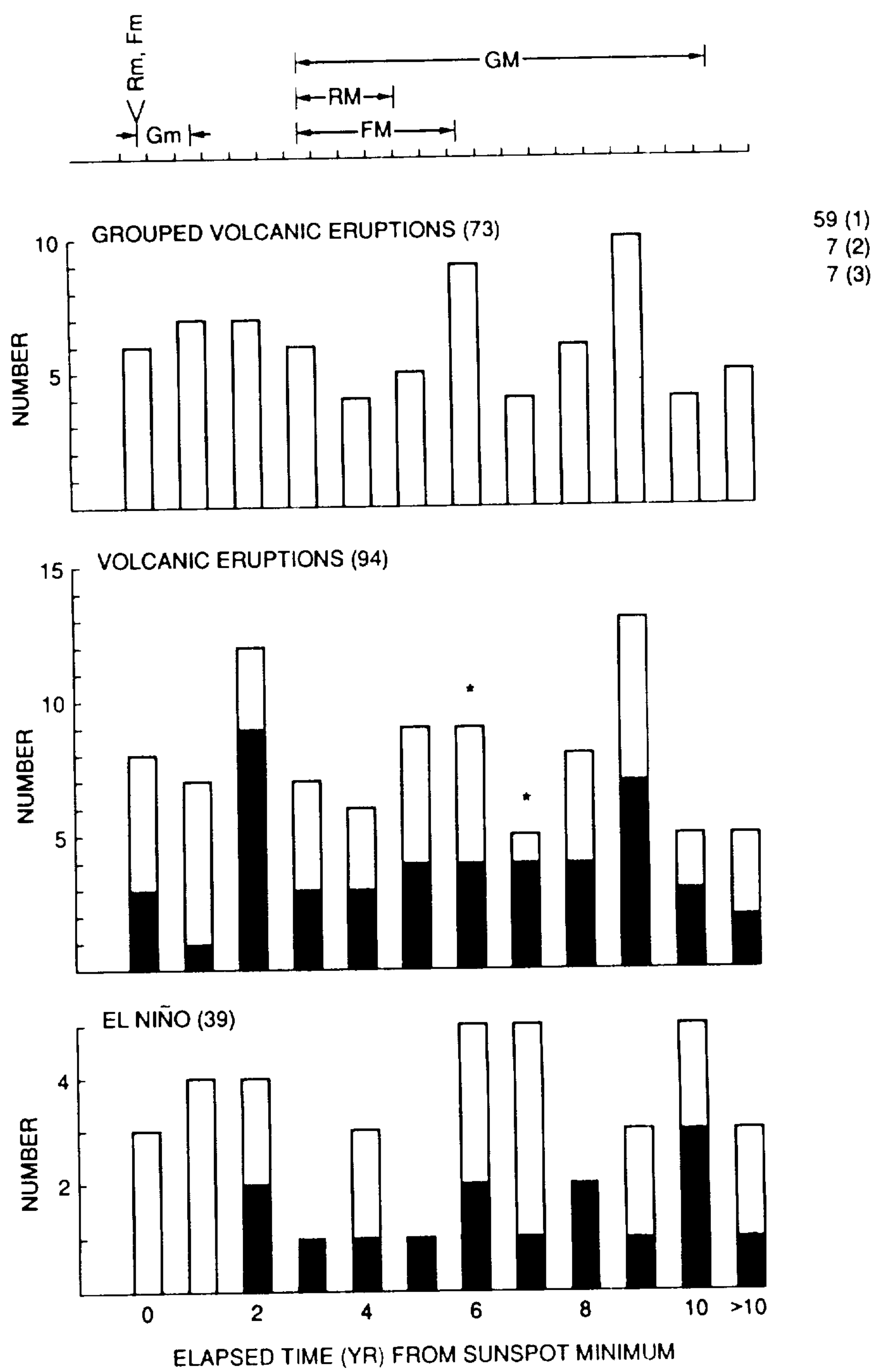

Figure 8. Number of moderate to stronger El Niño events as a function of elapsed time (in years) from sunspot minimum (bottom), where shading denotes El Niño events of strong intensity; number of major individual and "grouped" volcanic eruptions as a function of elapsed time (in years) from sunspot minimum (middle and upper panels), where shading in the middle panel denotes tropical eruptions; milestones relating to the solar/geomagnetic cycles are indicated across the top (see text for other details).

events of 1982 and 1983 have been included as tropical eruptions). Above this is a histogram of the 73 "grouped" occurrences of major volcanic eruptions, where a "grouped" eruption refers to same year multiple eruptions. Across the top are major milestones during the sunspot/geomagnetic cycles, with Fm, Gm, and Rm referring to minimum values of the radio, geomagnetic, and sunspot indices, respectively, and FM, GM, and RM referring to their respective maximum values. A casual comparison of El Niño onsets and volcanic eruptions (the bottom two panels) suggests striking similarity, especially if one incorporates a lag of 1 year between volcanic eruption (cause) and El Niño onset (effect); in particular, peaks of El Niño activity usually follow by 1 year peaks of volcanic activity. Hence, volcanic activity may be the dominant causative factor in climatic change, although the sunspot/geomagnetic cycles seem to play a partial role as well. As a future activity, it would be interesting to compare monthly or seasonal values of solar/geomagnetic data with respect to El Niño onsets.

V. SUMMARY

The major findings of this investigation can be summarized as follows: Onsets of moderate to stronger El Niño have occurred at the rate of about one every three to four years, on average, having a range of one to eight years. Moderate events have occurred more frequently than strong events and there has never been a single occurrence of two strong events in succession. Elapsed times between successive onsets may be described using the normal distribution, although a positive skew is apparent, with greater variation since about 1917 than before. Onsets of El Niño usually occur during southern hemispheric summer/fall (December-May) and, as yet, none has occurred during southern winter (June-August). Major, tropical volcanic activity (assuming that they inject large quantities of aerosols into the stratosphere that persist up to 3 years) can only account for about 70 percent of the El Niño events, although major volcanic activity, in general (ignoring latitude), can "explain" about 85 percent of the El Niño events. For some unknown reason, moderate El Niño events appear to preferentially occur in the vicinity of sunspot minimum and when annual sunspot number is low, especially when it is below 45.3 (the median value), while strong El Niño events appear to preferentially occur during the declining portion of the sunspot cycle. A possibly significant inverse correlation is inferred to exist between the number of El Niño events per sunspot cycle and the size of the sunspot cycle, suggesting that during the Maunder minimum (1645 to 1715) more El Niño events took place than take place today and that during the next several sunspot cycles (assuming a continued increase in sunspot number with time, modulated by the Gleissberg cycle) fewer events per sunspot cycle might be expected. Finally, one infers that 10.7-cm solar radio flux, the aa and Ap geomagnetic indices, and solar irradiance are all directly correlated with sunspot number, although the geomagnetic cycle usually lags the sunspot cycle by 1 year, and the maxima for the other indices sometimes differ markedly, with geomagnetic maximum occurring about 6 years into the cycle (or about 2 years past sunspot maximum during the declining portion of the sunspot cycle).

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16. Abstract

El Niño is conventionally defined as an anomalous and persistent warming of the waters off the coasts of Ecuador and Peru in the eastern equatorial Pacific, having onset usually in southern hemispheric summer/fall. Examined here are some of the statistical aspects of El Niño occurrences, especially as they relate to the normal distribution and to possible associations with volcanic, solar, and geomagnetic activity.

With regard to the "very strong" El Niño of 1982–83, it is noted that, although it may very well be related to the 1982 eruptions of El Chichón, the event occurred essentially "on time" (with respect to the past behavior of elapsed times between successive El Niño events: a moderate-to-stronger El Niño was expected during the interval 1978 to 1982, assuming that El Niño occurrences are normally distributed, having a mean elapsed time between successive onsets of 4 years and a standard deviation of 2 years and a last known occurrence in 1976). Also, although not widely recognized, the whole of 1982 was a record year for geomagnetic activity (based on the aa geomagnetic index, with the aa index registering an all-time high in February 1982), perhaps, important for determining a possible "trigger" for this and other El Niño events.

A major feature of this study is an extensive bibliography (325 entries) on El Niño and volcanic-solar-geomagnetic effects on climate. Also, included is a tabular listing of the 94 major volcanic eruptions of 1835 to 1986.

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